

TITLE
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Constraints on the equation of state of ultra-dense matter from observations of neutron stars

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Abstract. I discuss constraints on the equation of state of matter at supra-nuclear densities that can be derived from observations of neutron stars. I focus on recent work on Vela X-1, which may well be substantially more massive than the canonical $1.4 M_{\odot}$, and on the prospects offered by the ‘isolated’ or ‘thermally-emitting’ neutron stars.

1. The equation of state for ultra-dense matter

To understand the core collapse of massive stars, the supernova phenomenon, and the existence and properties of neutron stars, requires knowledge of the equation of state (EOS) for matter at supra-nuclear density. The EOS is determined by the behaviour of elementary particles at close proximity to each other and hence is of fundamental physical interest. It is modeled using quantum-chromodynamics calculations, but these are not developed well enough to determine the densities at which, e.g., meson condensation and the transition between the hadron and quark-gluon phases occur. At densities slightly higher than nuclear and at high temperatures, the model predictions can be compared with the results of heavy-nuclei collision experiments. For higher densities and low temperatures, however, this is not possible; the models can be compared only with neutron-star parameters. Recent reviews of our knowledge of the EOS, and the use of neutron stars for constraining it, are given by Heiselberg & Pandharipande (2000), Lattimer & Prakash (2000, 2001), and Balberg & Shapiro (2000).

The different models for the EOS predict highly different mass-radius relations, and a direct constraint on the EOS would be set by a simultaneous measurement of the radius and mass of a neutron star. This has not yet been possible, and observational tests have been limited to predictions for extrema, such as the maximum possible mass and the minimum possible spin or orbital period. For instance, for EOS with a phase transition at high densities, such as Kaon condensation (Brown and Bethe 1994), only neutron stars with mass $< 1.5 M_{\odot}$ could exist (for larger masses, a black hole would be formed).

So far, susceptibility to systematic errors and modeling uncertainties have befuddled most attempts to constrain the EOS observationally (e.g., radius determinations from X-ray bursts, Lewin et al. 1993; innermost stable orbit from kHz QPOs, Van der Klis 2000). The only accurate measurements are the fastest spin period and some precise masses. The former, 1.5 ms, excludes the stiffest EOS (PSR B1937+214; Backer et al. 1982); the latter I discuss below.

2. Neutron star masses

Most mass determinations have come from radio timing studies of pulsars; see Thorsett & Chakrabarty 1999 for an excellent review. The most accurate ones are for pulsars that are in eccentric, short-period orbits with other neutron stars, such as the Hulse-Taylor pulsar PSR B1913+16, in which several non-Keplerian effects on the orbit can be observed: the advance of periastron, the combined effect of variations in the second-order Doppler shift and gravitational redshift, the shape and amplitude of the Shapiro delay curve shown by the pulse arrival times as the pulsar passes behind its companion, and the decay of the orbit due to the emission of gravitational waves. Thorsett & Chakrabarty found that for all radio-pulsar binaries, the masses were consistent with being in a surprisingly narrow range, which can be approximated with a Gaussian distribution with a standard deviation of only $0.04 M_{\odot}$. The mean of the distribution is $1.35 M_{\odot}$, close to the “canonical” value of $1.4 M_{\odot}$.

Neutron-star masses can also be determined for some binaries containing an accreting X-ray pulsar, from the amplitudes of the X-ray pulse delay and optical radial-velocity curves in combination with constraints on the inclination (the latter usually from the duration of the X-ray eclipse, if present). This method has been applied to about half a dozen systems (Joss & Rappaport 1984; Nagase 1989; Van Kerkwijk, Van Paradijs, & Zuiderwijk 1995b). The masses are generally not very precise, but are consistent with $\sim 1.4 M_{\odot}$ in all but one case.

The one exception is the X-ray pulsar Vela X-1, which is in a 9-day orbit with the B0.5 Ib supergiant HD 77581. For this system, a rather higher mass of around $1.8 M_{\odot}$ has consistently been found ever since the first detailed study in the late seventies (Van Paradijs et al. 1977; Van Kerkwijk et al. 1995a). A problem with this system, however, is that the measured radial-velocity orbit, on which the mass determination relies, shows strong deviations from a pure Keplerian radial-velocity curve. These deviations are correlated within one night, but not from one night to another. A possible cause could be that the varying tidal force exerted by the neutron star in its eccentric orbit excites high-order pulsation modes in the optical star which interfere constructively for short time intervals.

We have obtained about 150 new spectra, taken in as many nights, of the optical counterpart, a B supergiant, in order to improve the mass determination (Barziv et al. 2001). These cover more than 20 orbits, and make it possible to average out the velocity excursions. Unfortunately, however, we found that the average velocity curve shows systematic effects with orbital phase (see Fig. 1), which dominate our final uncertainty. While our best estimate still gives a high mass, of $1.86 M_{\odot}$, the 2σ uncertainty of $0.33 M_{\odot}$ does not allow us to exclude soft equations of state conclusively.

While we cannot draw a firm conclusion, it is worth wondering how Vela X-1 could be the only neutron star with a mass so different from all others. Barziv et al. (2001) discuss this in some detail and warned against taking the narrow mass range around $1.4 M_{\odot}$ as evidence for an upper mass limit set by the EOS. After all, for all EOS, neutron stars substantially *less* massive than $1.4 M_{\odot}$ can exist, yet none are known. Could it be that the narrow range in mass simply reflects the formation mechanism, i.e., the physics of supernova explosions and

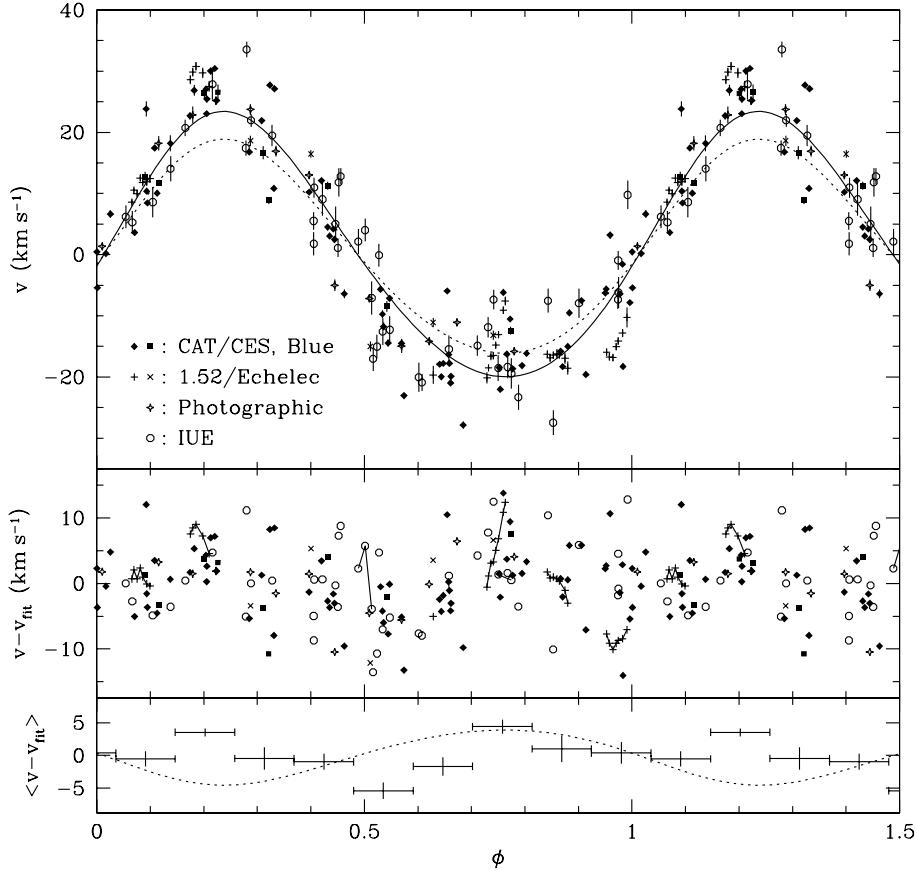


Figure 1. Radial-velocity measurements for HD 77581, the optical counterpart to Vela X-1. Overdrawn is the Keplerian curve that best fits the nightly averages of the data (solid line; $K_{\text{opt}} = 21.7 \pm 1.6 \text{ km s}^{-1}$), as well as the curve expected if the neutron star has a mass of $1.4 M_{\odot}$ (dotted line; $K_{\text{opt}} = 17.5 \text{ km s}^{-1}$). The residuals to the best-fit are shown in the middle panel. For clarity, the error bars have been omitted. Points taken within one night are connected with lines. In the bottom panel, the residuals averaged in 9 phase bins are shown. The horizontal error bars indicate the size of the phase bins, and the vertical ones the error in the mean. The dotted line indicates the residuals expected for a $1.4 M_{\odot}$ neutron star.

the evolution of stars massive enough to reach core collapse? There certainly is precedent: white dwarfs are formed with masses mostly within a very narrow range around $0.6 M_{\odot}$, well below their maximum (Chandrasekhar) mass.

Interestingly, from evolutionary calculations, Timmes et al. (1996) expect that single stars produce neutron stars with a bimodal mass distribution, with peaks at 1.27 and $1.76 M_{\odot}$. For stars in binaries, they found only a single peak at $\sim 1.3 M_{\odot}$, but at present it is not clear whether this result will hold (Woosley 2000, private communication). If not, could it be that the progenitor of Vela

X-1 was a star that managed to produce a massive neutron star? If so, one may still wonder why no massive radio pulsars or pulsar companions have been found. Barziv et al. (2001) noted that this may be a selection effect: all neutron stars with accurate masses are in binary neutron stars systems in close orbits, whose formation requires a common-envelope stage. During this stage, a merger can only be avoided if the initial orbit was very wide. Stars massive enough to form a massive neutron star, however, likely do not evolve through a red-giant phase, and a common-envelope phase would occur only for rather close orbits, for which the binary would merge.

Finally, in considering the present mass measurements, one should realise that for all neutron stars with good masses, it is expected that they accreted only little mass after their formation. Only neutron stars in low-mass X-ray binaries and radio pulsars with low-mass white dwarf companions are expected to have accreted substantial amounts of material. For low-mass X-ray binaries, higher masses, of $\sim 2 M_{\odot}$, have indeed been suggested; see, e.g., Orosz & Kuulkers (1999) for an analysis of Cyg X-2, and Zhang et al. (1997) for inferences based on quasi-periodic oscillations. These estimates, however, rely to greater or lesser extent on unproven assumptions. Furthermore, for the putative descendants, radio pulsars with white dwarf companions, there is no evidence for such high masses (Thorsett & Chakrabarty 1999 and references therein; Van Straten et al. 2001).

3. Neutron star atmospheres

Spectroscopic measurements of absorption lines arising in the photosphere of a neutron star offer, in principle, one of the best possible ways to constrain the EOS, since one could measure both the gravitational redshift and pressure broadening, which go as M/R and M/R^2 , respectively (Paerels 1997). With the X-ray spectrographs on board *Chandra* and *XMM*, these measurements have become possible.

For spectroscopy to produce quantitative results, the following is required: (i) a source needs to have a thermal spectrum; (ii) the spectrum should show absorption lines; (iii) pressure broadening and pressure-induced wavelength shifts must be understood; (iv) it has to be possible to recognise and model sources of possible additional broadening and wavelength shifts (e.g., magnetic field). I discuss these points in turn.

3.1. Thermal, photospheric emission

For most neutron stars known, the X-ray emission is contaminated, if not dominated, by accretion or magnetospheric processes, which are poorly understood. Therefore, these are unsuitable targets.

The isolated, radio-silent neutron stars, however, appear to offer a good chance for measuring thermal, absorption spectra. Since the serendipitous discovery of the first of these in 1996 by Walter, Wolk, & Neuhauser, five more have been uncovered in the *ROSAT* All-Sky Survey (see the review by Treves et al. 2000). For two sources, optical counterparts have been identified (Walter & Matthews 1997; Motch & Haberl 1998; Kulkarni & Van Kerkwijk 1998). The

high X-ray to optical flux ratios leave no model but an isolated neutron star; stringent optical limits indicate the same for the other four sources.

At present, it is not clear why these neutron stars are hot enough to emit X rays, with slow accretion from the interstellar medium, residual heat, and decay of strong magnetic fields all being considered (e.g., Kulkarni & Van Kerkwijk 1998). Most important for the present purposes, however, is that all six sources appear to have spectra that, as far as one can tell from current observations, are entirely thermal. These sources, therefore, offer the best hope of spectra clean enough to have a chance of modeling them reliably.

Perhaps the best-suited target for detailed study is RX J1856.5–3754, the brightest steady, thermally emitting neutron star on the sky (Walter et al. 1996; Walter & Matthews 1997). Measurements over the optical to X-ray range indicate a spectral energy distribution very close to that of a black body, with $kT_\infty \simeq 50$ eV (Pons et al. 2001). There are some deviations, however, as indicated by, e.g., the slightly higher best-fit black-body temperature of 63 eV at X-ray energies (Burwitz et al. 2001). No non-thermal emission whatsoever seems to be present, given the lack of hard X-ray emission (Pons et al. 2001) and the remarkable extent to which the optical emission is described by a Rayleigh-Jeans tail (Van Kerkwijk & Kulkarni 2001a).

A possible puzzle is posed by the parallax of 16.5 ± 2.3 mas measured by Walter (2001), which, combined with the inferred temperature of ~ 50 eV and the observed flux, implies a radius of only $7(d/60\text{ pc})\text{ km}$ (Pons et al. 2001). This radius is impossible for *any* EOS. Pons et al. suggest the neutron star has a non-uniform temperature distribution. For the analysis of spectral lines, this may not a problem; more important is the absence of non-thermal emission.

3.2. Presence of absorption lines

Given clean, thermal emission, the next worry is whether the spectrum will not be too clean, i.e., whether it will show any lines. In the X-ray spectral range, this requires the presence of elements other than Hydrogen and Helium in the photosphere (unless very strong magnetic fields are present).

In general, one would expect that, if any Hydrogen is present, gravitational settling would make it float on top. This process is fast and thus a pure Hydrogen atmosphere might form, resulting in a line-less X-ray spectrum. Observationally, the situation looks promising: the spectral energy distributions of the two sources with optical counterparts are similar to those of black bodies. This is inconsistent with pure (unmagnetised) hydrogen or helium atmospheres, whose virtual transparency at X-ray wavelengths would lead – just as in, e.g., Sirius B – to strongly non-black-body spectral shapes (Pavlov et al. 1996). Since models with solar abundance, pure iron, or ‘Si-ash’ abundances all predict strong absorption features (Romani 1987; Rajagopal & Romani 1996; Zavlin, Pavlov, & Shibakov 1996; Pons et al. 2001; Gängsche, Braje, & Romani 2001), the prospects looked good.

Reality, however, was disappointing: the first spectrum at good resolution, taken with *XMM* of RX J0720.4–3125 showed no features (Paerels et al. 2001). Furthermore, the spectra of the Vela pulsar and of PSR B0656+14, both of which have relatively strong thermal components, appeared to be completely featureless as well (Pavlov et al. 2001; H. Marshall, priv. comm.). And finally,

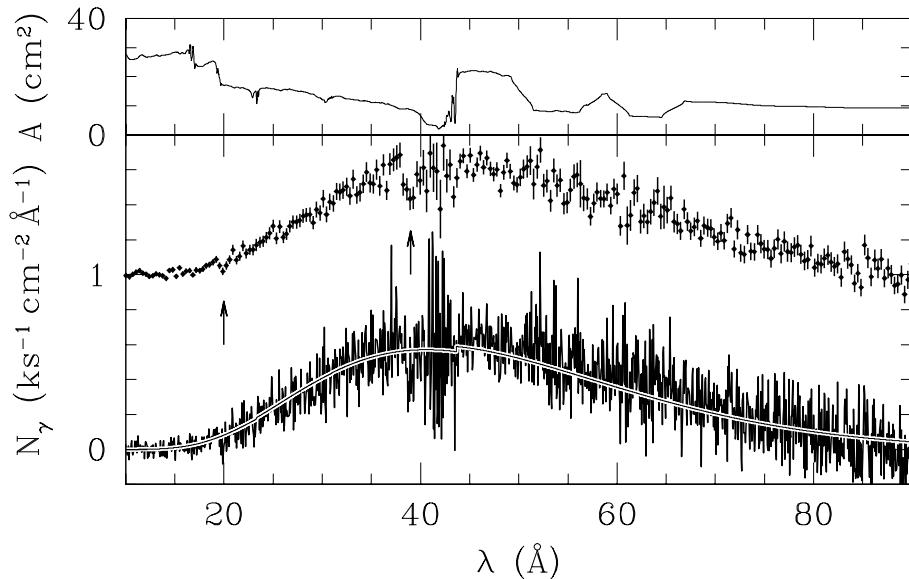


Figure 2. Presently available 56 ks LETG+HRC-S spectrum of RX J1856.5–3754, calibrated using effective areas determined at SRON/Utrecht (top panel). The top curve is binned to 0.34 \AA , the bottom one to 0.06 \AA . Overdrawn is the best-fit black-body as derived by Burwitz et al. (2001): $kT_\infty = 63 \pm 3 \text{ eV}$, $N_H = (1.03 \pm 0.20) \times 10^{20} \text{ cm}^{-2}$, $R_\infty/d = 0.037 \pm 0.005 \text{ km pc}^{-1}$. Unlike other neutron stars observed so far, there are absorption features! These are marked by arrows. The one at 39 \AA appears highly significant, while that at 20 \AA seems marginal. The longer integration currently planned in director’s discretionary time will allow to confirm (or not) their reality, as well as to detect other lines. If multiple lines are present, this spectrum may well provide the best constraint yet on the EOS.

also for RX J1856.5–3754, X-ray spectra taken with *Chandra* (Burwitz et al. 2001), ultra-violet spectra taken with *HST* (Pons et al. 2001), as well as optical spectra taken with VLT (Van Kerkwijk & Kulkarni 2001a) failed to show strong features.

The situation may not be completely hopeless, however, as our own analysis of the LETG data did turn up possible features, at ~ 39 and 20 \AA (Fig. 2). At present, it is not clear what these could be due to. As mentioned, pure Hydrogen and Helium atmospheres are excluded by the overall spectral shape, and pure heavy-element atmospheres by the lack of much stronger features. We have considered whether low-level accretion might lead to metals in the photosphere. This can be estimated using the density of the interstellar medium inferred from the cometary H α nebula around the source that we discovered with the VLT (Van Kerkwijk & Kulkarni 2001b), under the assumption that this nebula is due to ionisation (see below for an alternative interpretation). We infer an accretion rate of about 10^9 g s^{-1} . This is far less than required to power the X-ray luminosity of the source, and the photospheric metal abundances will be

very low, due to rapid settling. Even at fractional abundances by number of $10^{-7} \dots 10^{-6}$, however, it appears lines might still form, although it is unclear whether the continuum shape could be made to fit the observations.

In considering the above, one should realise that the current integrations have not been very long, and the signal-to-noise ratios rather low (see Fig. 2). Indeed, at the current signal-to-noise and resolution, it would be hard to classify an optical spectrum of a star like the Sun. In AO3, therefore, there were a number of proposals to obtain a longer *Chandra* observation on RX J1856.5–3754. None of these made it, but the director, H. Tananbaum, has just announced that he will use his discretionary time to observe the source for 450 ks. Hence, we should soon know more!

3.3. Model atmospheres

From absorption lines such as those seen in Fig. 2, it is straightforward to measure centroids accurate enough to determine a good gravitational redshift ($z_{\text{GR}} \simeq 0.3$). Furthermore, the lines are well resolved, and thus it should be possible to measure the pressure broadening and therewith the surface gravity.

First of all, however, one has to identify the lines. With the two putative lines in the spectrum of RX J1856.5–3754, this is not yet possible. Even with identifications, the interpretation may pose a problem, as our physical understanding may not suffice to make reliable predictions of pressure broadening and pressure-induced wavelength shifts. For instance, current treatment of overlapping Stark-broadened excitation levels (e.g., in the Opacity Project; Seaton et al. 1994) is *known to fail* even under the relatively low pressures encountered in white dwarfs (Bergeron 1993), leading to bad fits to Hydrogen Balmer and especially Lyman profiles (Finley et al. 1997), both for white-dwarf spectra and for spectra taken of high-pressure plasmas on Earth. Clearly, the fact that, as yet, we lack sufficient understanding of even Hydrogen, should lead to some moderation in ones claims. The problems do not appear to be of fundamental nature, however, and with *observed* features in neutron-star atmospheres, there should be ample incentive for further study.

3.4. Other physical effects

Strong magnetic fields ($h\nu_{\text{cyc}} > (kT, h\nu_{\gamma}) \Rightarrow B \gtrsim 10^9 \text{ G}$ at X-ray wavelengths), as are found in radio pulsars, could cause additional broadening and wavelength shifts. For RX J0720.4–3125 and RX J0420.0–5022, 8-s and 23-s periodicities (Haberl et al. 1997, 1999) provide indirect evidence for a magnetic field. Indeed, it may well be that these sources are middle-aged ‘magnetars,’ with $B \simeq 10^{14} \dots 10^{15} \text{ G}$, which are kept hot by magnetic field decay (Kulkarni & Van Kerkwijk 1998; Heyl & Kulkarni 1998).

For RX J1856.5–3754, very strong fields seem to be excluded by the absence of pulsations (Pons et al. 2001; Burwitz et al. 2001). A weaker field might nevertheless be present. Indeed, an alternative interpretation for the H α nebula around RX J1856.5–3754 is that it is a bow-shock nebula, such as seen around a number of pulsars (PSR B1957+20: Kulkarni & Hester 1988; PSR B2224+65: Cordes, Romani, & Lundgren 1993; PSR J0437–4715: Bell et al. 1995). If so, a relativistic wind must be present, which presumably arises in a magnetosphere. In order to avoid pulsations as well as any sign of non-thermal emission at

optical and X-ray wavelengths, one might appeal to a rather weak, few 10^{11} G field (Van Kerkwijk & Kulkarni 2001b). The question remains, however, whether the presence of such field, or a magnetic field in general, could lead to spectra as close to those of black bodies as observed.

A magnetic field might also induce absorption features. For instance, the ratio of roughly a factor two in wavelength between the two possible features we observe, led G. Pavlov (2000, priv. comm.) to speculate that they might represent proton and $A/Z = 2$ cyclotron lines in a strong, $\sim 10^{14}$ G field. If confirmed, the spectra will likely not be very useful to constrain the EOS, but it would constitute the first direct proof of an ultra-strong magnetic field in a neutron star.

4. Prospects

In the near future, it should be possible to increase the number of accurate neutron-star mass determinations substantially. For X-ray pulsars other than Vela X-1, it is straightforward to obtain better radial-velocity amplitudes. By choosing binaries with circular orbits, the problems that beset the mass determination for Vela X-1 can largely be avoided. For radio pulsars, of most interest seem to be those which should have accreted a substantial amount of matter, i.e., the millisecond pulsars. With only little improvement, optical studies of their companions such as those done by Van Kerkwijk, Bergeron, & Kulkarni (1996) and Callanan, Garnavich, & Koester (1998), and precise radio timing studies such as the marvellous work by Van Straten et al. (2001) can lead to accurate masses.

X-ray spectroscopy of neutron stars has just started, and has led to both disappointments and hope. The longer observations with *XMM* and *Chandra* currently planned, in particular the 450 ks LETG observation in director's discretionary time of RX J1856.5–3754, will certainly help to learn about neutron-star atmospheres. What exactly we will learn one cannot say, since at present we seem to lack even basic understanding, being unable to answer as (apparently) simple a question as why the spectra are so close to black bodies. Given that, it is also unclear whether this avenue can lead to useful constraints the EOS, but at least in principle the prospects are very good. Certainly, exciting times are ahead.

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